5G PPP

Test, Measurement and KPIs Validation WG

5G PPP Trials Results 2022 -
Key Performance Indicators measured in advanced 5G Trial Sites

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Executive Summary

As the 5G Public Private Partnership (5G PPP) has entered its last stage, and the 5G PPP Research and Innovation (R&I) projects and Working Groups (WG) are wrapping up their activities with a target end date at the end of 2023, it is important to record and analyse the trial findings and gained insights of the latest 5G PPP projects that engaged in 5G-enabled field trials. This white paper by the Test, Measurement and KPIs Validation (TMV) WG, provides the state of play of recently finished and still active projects from Phase 3 of 5G PPP, aggregates their field measurements, presents and analyses their 5G network (and application level) KPIs and discusses the gained insights, from the latest 5G PPP trials.

This white paper is a natural conclusion of the work of the TMV WG as presented in its previous white papers, which are summarized here along with the key achieved results of the WG, as it complements the recorded metrics and KPIs from previous 5G PPP phases with Phase 3 results. Additionally, it provides insights regarding the performance of state-of-the-art 5G features/technologies (e.g., 3GPP Rel. 16 SA), that were not available in previous trials, but have been validated during Phase 3 trials.

The results presented in this white paper are based on the work carried out by ***15 Phase 3 5G PPP R&I projects*** that engaged in 5G-enabled trials in 2022 and early 2023. These fifteen projects performed field measurement in ***36 distinct 5G Trial Sites***, constructed ***across 14 European countries***, during which a total of ***50 vertical use cases*** were tested and validated via the implementation of about ***80 distinct trial scenarios***. A large variety of diversified 5G technologies, features and settings were used across the different projects, covering outdoor and indoor scenarios as well as stationary and mobile, different operational frequency bands and 5G system releases, architecture and configurations, as well as complementary technologies. The extensive set of parameters and configuration used during the 5G PPP Phase 3 trials proves the versatility of 5G networks and offers cumulative insights with regards to the expected 5G performance in diversified scenarios.

The analysis of the trial results and the recorded KPIs indicates that the theoretical 5G target values for peak data rate and network latency have been validated in the field as data rates larger than 1 Gbps in the DL and 500 Mbps in the UL have been recorded, while the recorded Round Trip Time (RTT) in most trials remained under 30 ms. At the same time the enhanced performance of Stand Alone networks was also verified, as RTT latencies with SA were always measured at the interval 0-15 ms, while RTT latencies with NSA were measured in the interval 15-30 ms. Moreover, the recorded User experience data rate per addressed vertical service and the corresponding performance vs service matrix, provide significant insights with regards to the expected data rate per vertical service type and indicate that enhanced AR/VR services and AI/ML based data collection & processing services, are driving the future network requirements.

This white paper concludes the TMV WG’s reporting on 5G PPP trial KPIs, but the valuable experience gained, the lessons learned and best practices, accumulated over its long operation will be inherited by follow up R&I programmes.

1 Introduction

The 5G Public Private Partnership (5G PPP[1]) has been established in 2014 and since then has funded more than 93 Research and Innovation (R&I) projects all around Europe, fostering the development, testing, validation and improvement of 5G related technologies and verticals. As the entire 5G PPP programme was founded on the principle that the cumulative knowledge and insights gained through cross-collaboration of experts form different projects is greater than the sum of the individual projects' learnings, common thematic Working Groups (WGs) have been established, where experts from all around Europe and different projects gather to present and discuss the results of their respective work. As a result, a better understanding of the various technologies inter-workings and behaviour is achieved, leading to more spherical knowledge of the 5G system.

1.1 Scope

The Test, Measurement and KPIs Validation (TMV) WG is an integral WG of 5G PPP focusing on Test and Measurements procedures, tools, and methodologies (testing, monitoring, and analytics), and allowing experts to exchange best practices and results from the various 5G measurement campaigns within the 5G PPP programme. Currently the group is comprised by experts of the Phase 3 5G PPP projects [1], which are the only remaining active projects. The output of this WG is cross-validated results across multiple projects and platforms and cumulative insights gained on the measurement procedures and tools as well as the functionality and performance of different 5G technologies under varying scenarios, network configurations and environmental conditions. The TMV WG has already delivered significant work and insights based on the learnings from the tests, trials and pilots of the various 5G PPP projects over time (see Section 2.2 for more details). As the entire 5G PPP programme, and with it the TMV, approaches its finalization at the end of 2023, it is important to report on the measured Key Performance Indicators (KPIs) of the latest Phase 3 projects and to attempt to understand the behaviour of the 5G networks used for the trials under a varying set of parameters, environmental conditions, and configurations.

1.2 Motivation

As the final phase of 5G PPP is currently ongoing, several ongoing projects from Phase 3.2 [2], Phase 3.3 [3], Phase 3.4 [4], Phase 3.5 [5] and Phase 3.6 [6] have either just concluded or are finalizing their Trials & Pilots using state of the art advanced 5G testbeds and/or trial sites. The development and deployment of these 5G trial sites and testbeds required a significant amount of effort and time from the project participants and

[1] https://5g-ppp.eu/

constitute unique infrastructures across Europe allowing for real-life 5G-enabled trials under varying conditions and for different vertical use cases (UC).

This White Paper expands on the work presented in previous TMV white papers (see Section 2.2) and reports the latest KPIs as measured during trials that took place in 2022 (and early 2023) in fifteen (15) 5G PPP Phase 3 projects. These projects performed their measurements, using state of the art 5G technologies and features (e.g., up to 3GPP Rel.16 Stand Alone (SA) networks) and cover an extensive set of trial scenarios, 5G network configurations and geo-environmental conditions. Even though the reported KPIs cannot be directly compared due to the widely different measurement conditions, they still provide significant insights with regards to the expected performance of 5G in various scenarios, and the expected range of values for some main KPIs (measured across all trials), while they also contribute to the better understanding of the observed 5G network behaviour.

The remainder of this paper is structured as follows. Section 2 provides an overview of the state of the art of the trials that have taken place within the 5G PPP ecosystem over the years while Section 3 provides the context for the work presented in this paper by presenting an overview of the fifteen projects that contributed with their trial measurements as well as an analysis of the used testbeds/trial-sites, 5G system properties and the addressed use cases and respective verticals. Section 4 presents the trial measurements from the various projects focusing on selected main KPIs and provides an analysis of the observed performance in the scope of selected scenarios and services, along with insights into future services and performance trends. Section 5 concludes this white paper with the aggregate insights and lessons learned. Finally, the detailed parameters per project and per trial scenario for all presented measurements/KPIs are provided in Appendix – Trial Scenarios.

2 5G PPP Trials State of the Art

2.1 5G PPP Trials History and Overview

Launched in 2014, the 5G PPP has funded 93 R&I projects, divided into three major phases, involving over 700 beneficiaries. The initiative has contributed to over 800 standardisation activities, produced over 2000 scientific publications and 40 whitepapers and drove 445 innovations. Each phase has targeted different technologies, infrastructures, devices, and verticals, namely:

- *Phase 1* of 5G PPP began in 2015 and included 19 projects which achieved significant advancements in 5G technologies, including spectrum requirements, evaluation, candidate bands, flexible RAN, network management, and security.
- *Phase 2* started in 2017 and brought in 21 new 5G PPP projects focusing on areas such as 5G flexible RAN, novel radio systems, multi-tenant control plane, slicing control, vertical experimentation, trials and pilots.
- *Phase 3* is ongoing since 2018 and has already seen achievements in various areas such as cellular systems, architecture, network management and orchestration, software networks, security, and privacy, as well as trials and pilots in 10 different verticals, including Industry 4.0, Agriculture and Agrifood, Automotive, Smart Cities and Utilities, and eHealth and Wellness, among others.

This paper focuses on phases 3.2, 3.3, 3.4, 3.5, and 3.6, and more specifically on projects that carried out real-life trials using 5G networks (trial sites) to measure related KPIs. As this effort is part of the TMV WG it contributes to providing confidence to Mobile Network Operators (MNO) and Verticals on deployed capabilities and services. The group aims to bridge the gap in doing E2E and NFV/VNF characterisations and performance evaluations in the new 5G infrastructure to identify specific areas in relevant standards bodies where projects should contribute.

2.2 5G PPP TMV WG achieved results & highlights

Since its establishment, the TMV WG has been focused on the whole lifecycle of 5G PPP KPIs, starting from the KPIs definition, metrics / KPIs collection and analysis and finally trying to produce insights by analysing results coming from different 5G PPP projects (addressing different verticals and executing trials with different technologies and deployment options).

In this direction, the TMV WG produced several whitepapers presenting KPI related 5G PPP projects' results, while time and effort were allocated in order to provide insights based on project feedbacks. The main whitepapers are listed in Table 1, in which the title, publication date, summary and highlights of each whitepaper are presented.

Table 1: TMV WG Whitepapers

#	Title Publication date [ref]	Summary & Highlights
1	**Validating 5G Technology Performance Assessing 5G architecture and Application Scenarios** June 2019 [7]	The whitepaper tries to be a first step into providing a more clear and homogeneous view over a list of 5G test and measurements topics, that will be briefly introduced and clarified. The idea is to establish a unified vision on the topics, allowing for common procedures and terminology. This is considered to be beneficial not only the 5G PPP infrastructure owners, but the entire 5G ecosystem.
2	**Service performance measurement methods over 5G experimental networks** May 2021 [8]	This white paper analyses the 5G PPP projects' use cases of various verticals for their performance KPIs and their mapping to the 5G network KPIs. The scope is to identify (based on architectural elements, information flow, etc.) the potential impact on the service performance and the perceived user quality. The considered vertical domains are: Smart Cities & Utilities, Transportation, Automotive, Media & Entertainment, Agriculture & Agri-food, Smart (Air)ports, Energy and E-health & Wellness. The goal was to understand the relationship between the 5G network performance indicators and the vertical services.
3	**Understanding the Numbers - Contextualization and Impact Factors of 5G Performance Results** June 2021 [9]	In this whitepaper, two main questions are answered: a) are the results close to the 5G theoretical values and the KPI targets promised by the 5G domain? b) can we identify some factors that practically affects the results, while others don't. Therefore, in this white paper the effort is focused on trying to clarify the details behind the performance numbers and provide a series of interpretation guidelines that could help the reader better understand the 5G domain. In addition, based on the analysis of performance results, the main impact factors that affect the results are identified, while a high-level explanation is provided that is clearly understandable by non-experts.
4	**Basic Testing Guide - A Starter Kit for Basic 5G KPIs Verification** Nov. 2021 [10]	This Basic Testing Guide document is a practical guide describing the starter kit developed in the context of the TMV WG. The guide enables the interested developer to understand how this can be applied to measure and verify basic 5G KPIs. The document starts from describing the idea intention to measure up to the actual realization of the test. To enable the test, a description of the environment, how to install it, the test tools and the methodology is provided.
5	**Beyond 5G/6G KPIs and Target Values** June 2022 [11]	The main objective of this document is to present the current view of the available B5G and 6G KPIs from 5G PPP phase III projects with a focus on projects of the ICT-52 call. This view includes mapping to KPIs previously defined for 5G and evaluating how they might evolve to fit the B5G and 6G visions. The paper consists of two main technical parts. The first part gives an overview of standard network KPIs with defined target values for 5G system. The second part presents KPIs collected from ICT-52 research projects aimed at B5G and 6G system. These KPIs are processed in terms of being grouped according to KPI type or context, and they are presented with references to standards and target values where possible and available.

6	**KPIs Measurement Tools - From KPI definition to KPI validation enablement** May 2023 [12]	This white paper summarizes the 5G Key Performance Indicators (KPIs) and the tools that have been identified and utilized in several ICT-17, ICT-19, and ICT-52 projects. The tools recognized in the different projects are presented, including open-source, ad-hoc developed and proprietary tools. Each tool is presented, highlighting the main functionalities and the list of KPIs that can be measured. Finally, the platforms for data collection and the tools for visualization are reported, highlighting their features and the availability of plugins/APIs to connect other tools/frameworks.
7	**B5G/6G KPI Monitoring** June 2023 [13]	B5G/6G is envisioned to bring a variety of new services and to the end user with faster transmissions, massive connectivity, lower latency, and higher reliability. This whitepaper presents a list of methodologies for monitoring and validation of B5G/6G KPIs, trying to ensure that the services provided by B5G/6G will work and fulfil certain requirements experienced by the end user in certain network scenarios.

In the first whitepaper, during the start of ICT-17 projects, the 5G trials challenges were defined and the common framework for KPI definition, testing and monitoring procedures and results collection, analysis and validation, was set. Since the trials were realised in various vertical environments, what was also important was to relate this common framework and approach with the verticals and their actual needs. In this direction, the vertical UCs of various domains were analysed for their performance KPIs, and they were mapped to 5G network KPIs (reported in the second whitepaper).

In addition, and since at that time mature results existed from the ICT-17 projects and initial results from some ICT-19 projects, it was decided to collect these results, to analyse them, and to provide interesting insights from the 5G trials. The results of this work are presented in the third whitepaper, which is in practice the predecessor of the current whitepaper. Therefore, in the third whitepaper the 5G PPP trial activities up to the ICT-17 projects were covered, while in this current whitepaper insights are presented from the ICT-18 and ICT-19 projects and onwards (until the end of the 5G PPP framework).

In order for the 5G PPP projects to become familiar with 5G testing and monitoring tools, in the TMV WG a basic software starter kit for 5G KPIs verification was developed. This tool together with a practical manual describing how to install and use it (step by step) are included in the fourth whitepaper.

Finally, in order to complete the addressed 5G topics, a whitepaper was generated which listed the 5G tools used in the 5G PPP projects from KPI monitoring and validation. The importance of the whitepaper stems from the fact that the majority of B5G/6G KPIs is an evolution of 5G KPIs, therefore the required tools for B5G/6G validation will be an extension/update of the current 5G Tools.

At that point, a move was performed from the 5G era to the B5G/6G era following the 5G PPP project path. A start was made from the first steps of the KPIs/results lifecycle which are: a) the definition of the KPIs and B5G/6G terminology and b) the identifications of the methodologies and tools for collecting and analysing the metrics and validating the results. The first step (a) is illustrated in the fifth whitepaper, while the second step (b) is presented in the last whitepaper published in June 2023.

3 5G PPP Trials Overview 2022

This Section provides an overview of the 15 active (or recently finished) 5G PPP projects that executed trials within 2022 (and early 2023) using 5G-enabled trial sites/testbeds. An overview of the scope of the projects is provided as well as statistics regarding the location of the 5G trial sites, the addressed verticals and use cases and the 5G system properties and technologies used in the trials. As such, a high-level view of the trialling landscape in the late 5G PPP programme phase is provided, along with the context for the measurements and KPIs reported in Section 4.

3.1 5G PPP project trials in 2022 – early 2023

The fifteen projects that carried out trials in the latest phase of 5G PPP and provided measurement data for this paper, originate from seven different H2020 calls, addressing a diversified portfolio of UCs and verticals, and using different 5G system versions, features and technologies. These projects performed 5G based trials to gain insights, not only on the expected benefits of 5G-enabled solutions for certain verticals/UCs, but also to map out the expected performance of 5G networks under a varying set of conditions and configurations. This paper aggregates the 5G network KPIs recorded during the trials of all these projects and analyses the reasons that lead to diversified 5G performance, depending on the scenario and configuration. Some of these projects have ended and have presented detailed results in their dedicated deliverables, while other projects are ongoing.

Table 2 provides an overview of the fifteen 5G PPP projects that performed trials and contributed their data for this white paper. Additional details per project can be found in their linked dedicated webpages.

Table 2: Overview of 5G PPP Phase 3 contributing projects

H2020 Call	Project	Focus	Duration
Phase 3.2 ICT-18-2018	5GCroCo [14]	Automotive Projects	Nov ’18 – Jul ‘22
	5G-MOBIX [15]		Nov ’18 – Oct ‘22
Phase 3.3 ICT-19-2019	5G-TOURS [16]	Advanced 5G validation trials across multiple vertical industries	Jun ’19 – Jul ‘22
	5G!DRONES [17]		Jun ’19 – Nov ‘22
	5G-HEART [18]		Jun ’19 – Nov ‘22
	5G-VICTORI [19]		Jun ’19 – Jun ‘23
Phase 3.4 ICT-20-2019	5G-COMPLETE [20]	5G Long Term Evolution	Nov ’19 – Oct ‘23
Phase 3.5 ICT-42-2020	5G-RECORDS [21]	5G Core Technologies innovation	Sep ’20 – Sep ‘22
	INT5GENT [22]		Nov’20 – Oct ‘23
Phase 3.5 ICT-53-2020	5G-Blueprint [23]	5G for Connected and Automated Mobility (CAM)	Sep’20 – Sep ‘23
Phase 3.6 ICT-41-2020	5GASP [24]	5G innovations for verticals with third party services	Jan ’21 – Dec ‘23
	5G-EPICENTRE [25]		Jan ’21 – Dec ‘23
	VITAL-5G [26]		Jan ’21 – Dec ‘23
Phase 3.6 ICT-52-2020	DAEMON [27]	Smart Connectivity beyond 5G	Jan ’21 – Dec ‘23
	REINDEER [28]		Jan ’21 – Jun ‘24

3.2 5G PPP Trial sites across Europe

The 15 projects that contributed to this white paper performed trials in advanced trial sites/testbeds across Europe, utilising the latest technologies and equipment. These trial sites represent diverse environments, from urban areas to rural regions, from lab scale deployments to deployments in operational environments, ensuring the versatility and scalability of the 5G networks being tested, and the reliability of the cumulative observations. Multiple trial sites per project enabled extensive data collection on network performance and user experience. Overall, 5G enabled trials took place in 2022 and early 2023 in **36 trials sites** located in **14 different European countries**, showcasing the widespread conduction of 5G research activities across Europe.

Figure 1 below depicts the distribution of these trial sites, illustrating how they are spread across the continent and highlighting the areas where 5G has already made a significant impact.

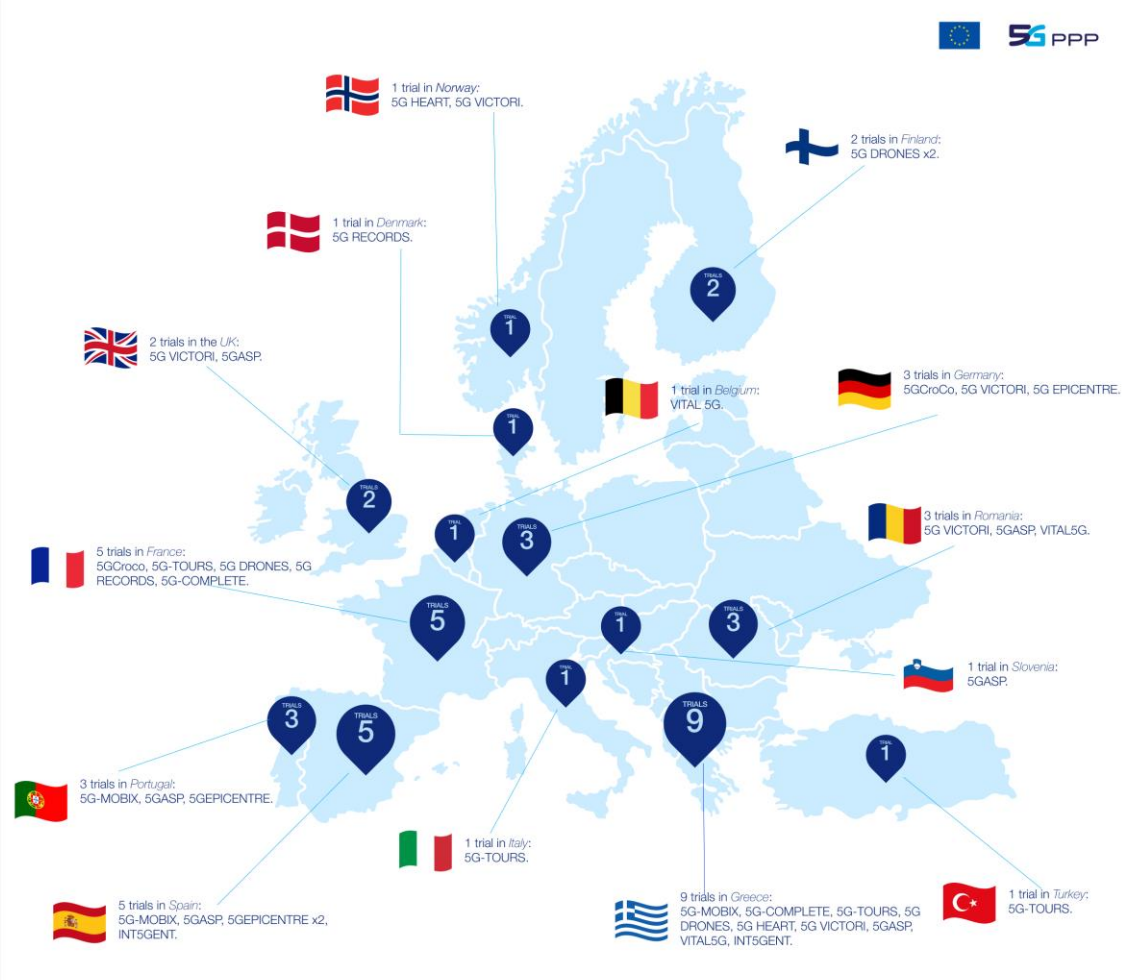

Figure 1:Overview of the 5G PPP active Trial Sites in 2022-2023

3.3 Targeted verticals and use cases

The 5G R&I projects under scrutiny in this study address several vertical sectors (and sub-sectors) - including automotive, smart health, security/PPDR, smart city, industry/ smart factories, tourism, media/XR, smart agriculture, smart home, and UAV/drones - engaged by different target UCs which provide insights into the specific areas where 5G technology is being applied. Figure 2 below provides an overview of the verticals addressed within the contributing 5G PPP projects.

As it can be observed, the Automotive/Transport sector leads with ten UCs homogeneously spread across different projects. Their common trend is the focus on improving mobility and transportation, promoting the concept of a touristic, safe, and mobility-efficient city. For example, the 5GCroCo project addresses teleoperated driving, HD maps for autonomous driving, and cooperative collision avoidance. The 5G-MOBIX project tackles automated overtaking and extended sensors. 5GASP, as a later phase 5G PPP project considers services such as C-ITS and digital twinning in automotive. The 5G-TOURS project promotes a touristic, safe, and mobility-efficient city. The 5G!DRONES project focuses on UAV traffic management, public safety, situation awareness, and crowded events connectivity. Finally, the 5G-HEART project addresses aquaculture.

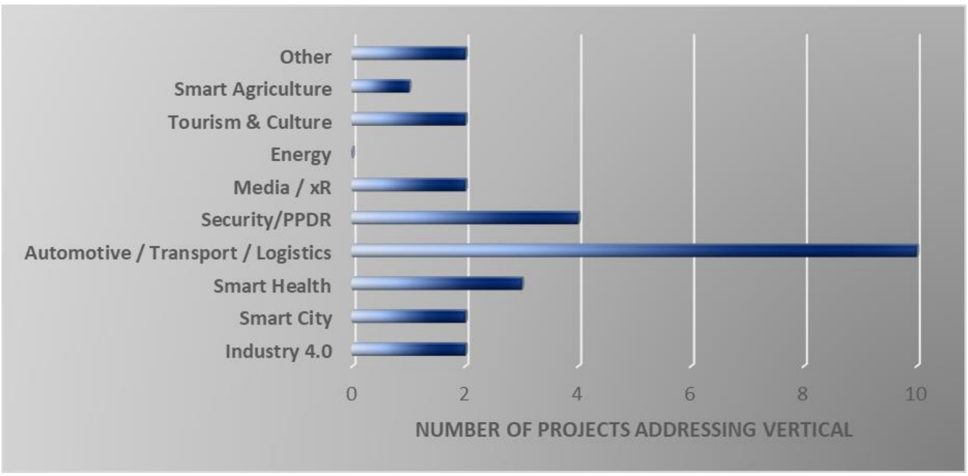

Figure 2: Verticals addressed in 5G PPP 2022 -early 2023 Trials

Three projects addressing the automotive sector - 5G-TOURS, 5G-VICTORI and REINDEER - also present UCs targeting automotive-related sectors such as Smart City (1), Smart Health (3) and Tourism & Culture (2). Both the Smart City and Tourism & Culture verticals are indissolubly related to the automotive vertical, with UCs linked to energy optimisation, immersive entertainment for crowds of people, and immersive media and AR/VR for travellers.

The Smart Health vertical, targeted by 5G-TOURS, 5G-HEART and REINDEER, is also loosely linked to the transportation verticals, emphasising urban safety, assisted living and human-machine interaction in care environments. The same applies to Smart Agriculture, with one UC on aquaculture targeted by 5G-HEART. REINDEER and 5G-VICTORI are also the only projects targeting the Industry 4.0 vertical, with UCs in factories of the future and adaptive robotised factories, warehouses and logistics.

The Security/PPDR vertical also presents six UCs– either directly as a separate sector, or as a sub-sector being part of other vertical sectors such as Transportation, automotive, smart-cities/ smart health, etc. Two of these are from projects also targeting the automotive sector, 5GASP and 5G-VICTORI. These are PPDR UCs related to railway services, cooperative mobility and automotive services in general. 5G-EPICENTRE, Int5Gent and 5G-COMPLETE are targeting the Security/PPDR vertical in various contexts/ use cases/ verticals, with UCs on drone navigation reliability, fast situational awareness, advanced surveillance and near real-time disaster mapping. These projects focus on other verticals such as Smart Health, with UCs on multimedia MC communication, multi-agency / multi-deployment mission-critical communications and dynamic service scaling, IoT for improving first responders' situational awareness and safety, and more. The same applies to 5G!DRONES, a project targeting the UAV/Drones vertical, with one UC linked to the automotive sector, such as traffic management and three more on public safety, situational awareness and connectivity during crowded events.

5G-RECORDS on the contrary, does not address the automotive or transportation sector implicitly or explicitly, and focusses on UCs on live audio and multi-camera live production targeting the Media/XR vertical. The Media XR UCs are also addressed as cross-vertical UCs in the context of transportation-media and smart cities-media cross-vertical paradigms by 5G-VICTORI, 5G-TOURS, 5G-EPICENTRE.

Overall, the various UCs addressed by the projects highlight the versatility and potential of 5G technology across different vertical sectors. Table 3, provides a matrix of the vertical sectors and the corresponding UCs, addressed during the 2022 -early 2023 5G PPP Trials, as declared by the projects.[2]

[2] It must be noted that mapping between addressed verticals and UCs is not always as straight-forward as one-to-one mapping. Instead, it depends highly on the type of stakeholders involved in each UC and the scope of the delivered service, as cross-vertical applications are not uncommon, or services may be offered from one vertical to another (e.g., PPDR vertical provides services to Transportation).

Table 3: Matrix of addressed Use Cases per Vertical on 5G PPP Trials in 2022

Vertical Use cases												
Automotive/Transport												
Tele-Operated Driving (5GCroCro, 5G-Blueprint)	HD Maps for Autonomous Driving (5GCroCro)	Cooperative Collision Avoidance (5GCroCro)	Automated Overtaking (5G-MOBIX)	Extended sensors (5G-MOBIX)	Railway services (5G-VICTORI, INT5GENT)	Aquaculture (5G-HEART)	Immersive media and AR/VR for travellers (5G-VICTORI)	Automotive services (5GASP)	Cooperative Mobility (5GASP)	Automated barge control (5G-Blueprint)	FRMCS-Future Railway Mobile Communication Services (5G-VICTORI)	Mobility Efficiency (5G-TOURS)
Smart Health			**Security/PPDR**									
Safe city (5G-TOURS)	Aquaculture (5G-HEART)	Natural human-machine interaction in care environments, hospitals, and assisted living (REINDEER)	PPDR services (5GASP, INT5GENT)	Multimedia MC Communication and Collaboration Platform (5G-EPICENTRE)	Multi-agency and multi-deployment mission-critical communications and dynamic service scaling (5G-EPICENTRE)	Ultra-reliable drone navigation and remote control (5G-EPICENTRE)	IoT for improving first responders' situational awareness and safety (5G-EPICENTRE)	Wearable, mobile, point-of-view, wireless video service delivery (5G-EPICENTRE)	Fast situational awareness and near real-time disaster mapping (5G-EPICENTRE)	AR and AI wearable electronics for PPDR (5G-EPICENTRE)	AR-assisted emergency surgical care (5G-EPICENTRE)	Advanced Surveillance and Physical security services (5G-COMPLETE)
UAV/Drones				**Smart City**				**Tourism & Culture**		**Industry 4.0**		
UAV traffic management (5G!DRONES)	Public Safety (5G!DRONES)	Situation awareness (5G!DRONES)	Connectivity during crowded events (5G!DRONES)	Safe City/Mobility efficient city (5G-TOURS)	Low Voltage Energy Metering (5G-VICTORI)	Content Delivery Network services (5G-VICTORI)	Digital Mobility and public safety (5G-VICTORI)	Immersive entertainment for crowds of people (REINDEER)	Touristic city (5G-TOURS)	Adaptive robotised factories, warehouses, and logistics (REINDEER)	Factories of the Future (5G-VICTORI)	
Media/xR			**Other**							**Smart Home**	**Smart Agriculture**	
Live Audio (5G-RECORDS)	Multi-camera live production (5G-RECORDS)	vCDN services (5G-COMPLETE)	Compute-aware Radio Scheduling (DAEMON)	Energy-aware VNF Orchestration (DAEMON)	Automated Anomaly Response (DAEMON)	Multi-timescale Edge resource management (DAEMON)	Capacity Forecasting and In-backhaul support for service intelligence (DAEMON)	Self-learning MANO (DAEMON)	Reconfigurable Intelligent Surfaces (DAEMON)	Home automation and smart home systems (REINDEER)	Aquaculture (5G-HEART)	

3.4 5G System properties & features

As mentioned in Section 3.1 the fifteen projects and their respective trials address a wide variety of scenarios requiring the use of different 5G system settings, network configurations and trialling environments. As a result, the recorded 5G network KPIs may significantly differ due to the different trial settings. Thus, it becomes critical to be clear on the exact settings of each trial scenario (reported in the Appendix – Trial Scenarios) in order to understand the reported performance.

Even though this diversification of trial scenario settings does not permit a direct comparison of KPIs among the different trials, it allows for the coverage of a large number of scenarios not feasible to be covered within a single project. As such, the 5G PPP projects cumulatively address an extensive list of 5G-enabled scenarios and provide insights regarding the use of different system settings, 5G features and other accompanying technologies to boost performance as well as operation under varying environmental conditions, as summarized in Figure 3. Figure 3-a provides an overview of the 5G system settings used per project including the used 5G 3GPP release and the utilized spectrum. Figure 3-b presents some of the key scenario parameters used for the trials of each project including indoor/outdoor environment, mobility status and the number of User Equipment (UEs) used during trials. Finally, Figure 3-c provides an overview of the additional key technologies that were used (alongside 5G connectivity) to boost specific aspects of performance or to enable specific scenarios/use cases.

It has to be noted that some projects like REINDEER and DAEMON performed their trials is alternative environments, complementing the results of the field trials and as such they are not included in Figure 3. In detail, REINDEER addresses solutions deployed on B5G new wireless infrastructures tested mainly in the lab. DAEMON focuses on the intelligence of the network and the evaluation of a network intelligence plane and AI solutions rather than the evaluation of the network itself.

	5G SYSTEM PROPERTIES					
	3GPP Rel. 15 NSA	3GPP Rel. 15 SA	3GPP Rel. 16 SA	700 MHz	3.5 - 3.8 GHz	26 GHz
5GCroCo	✓				✓	
5GMOBIX	✓				✓	
5G-[illegible]	✓				✓	✓
5G!Drones	✓		✓		✓	
5G HEART	✓				✓	
5G VICTORI	✓		✓		✓	
5G Complete		✓			✓	
5GASP	✓		✓		✓	
5G-EPICENTRE	✓		✓		✓	✓
VITAL 5G			✓		✓	
5G RECORDS		✓			✓	
Int5Gent		✓	✓		✓	
5G BLUEPRINT			✓	✓	✓	
OVERALL RATING	8	3	7	1	13	2

a)

	SCENARIO PARAMETER					
	Outdoor	Indoor	Stationary	Mobile	Max Num Cells	Max Num UEs
5GCroCo	✓			✓	10	10
5GMOBIX	✓			✓	3	10
5G-[illegible]	✓	✓	✓	✓	3	22
5G!Drones	✓	✓		✓	3	20
5G HEART	✓		✓		1	3
5G VICTORI	✓		✓	✓	3	5 / 3000 M-IoT
5G Complete	✓	✓	✓		2	5
5GASP	✓	✓	✓	✓	2	3
5G-EPICENTRE	✓	✓	✓	✓	3	8
VITAL 5G	✓	✓		✓	3	4
5G RECORDS		✓	✓		1	3
Int5Gent	✓	✓	✓	✓	2	3
5G BLUEPRINT	✓			✓	4	1
OVERALL RATING	12	8	8	10		

b)

	OTHER TECHNOLOGIES			
	WiFi 6	GNSS-RTK	MEC / Edge	802.11P
5GCroCo		✓	✓	
5GMOBIX		✓	✓	
5G-[illegible]			✓	
5G!Drones	✓		✓	
5G HEART				
5G VICTORI	✓		✓	
5GASP			✓	✓
5G-EPICENTRE	✓		✓	
VITAL 5G			✓	
5G RECORDS			✓	
Int5Gent			✓	
5G BLUEPRINT				
OVERALL RATING	3	2	10	1

c)

Figure 3: Overview of a) 5G system settings, b) Key scenario parameters and c) additional key technologies used per project/trial.

4 5G PPP Trial Results – KPIs and Insights

In order to collect the trials information per 5G PPP project and realise a meaningful analysis, a template was prepared and circulated to the projects. The template includes not only result related fields, as this would lead to an enumeration of results without any possibility to identify interesting insights. On the contrary, the circulated template includes additional fields related to a) the UC and the context; b) the verticals addressed; c) the network deployment parameters (e.g., 3GPP Release, RAN parameters); d) the application deployment options (e.g., central/edge) and e) the environment of the trial (e.g., indoor/outdoor, number of UEs, number of Cells, mobility aspects). In addition, the template includes fields related with the methodology and tools used in each trial scenario for: a) metric collection; b) metric analysis; c) KPI generation and d) KPI validation. All the above information assisted in the realization of a structured analysis, to ensure that selected metrics/KPIs from different scenarios/projects are comparable and finally to generate interesting insights. The template was filled from **15 5G PPP Phase 3 projects**, aggregating results from **80 distinct trials scenarios** in total, enabling a 5G PPP project representative analysis.

The analysis is performed and presented per KPI, starting from a common basic set of KPIs and continues to other interesting scenario-specific KPIs. In each subsection, the KPI related cumulative results are presented, the analysis is explained, and a list of interesting insights are presented capturing various trial aspects including a) verticals addressed; b) technologies used; c) technological options adopted; d) environmental particularities; e) UC specificities. Finally, for each KPI, the outcome of the analysis on the tools and methodologies used in the trials is presented.

4.1 Peak Data Rate (Downlink - Uplink)

As mentioned before, the 15 projects performed trials and measurement campaigns on platforms and covered an extensive set of scenarios (15 scenarios summarised in this section), 5G network configurations and environments.

All 15 projects used state of the art 5G technologies and features (e.g., up to 3GPP Rel.16 Stand Alone (SA) networks) with various network configurations. In particular, the network configurations differentiated in terms of utilised frequency channel bandwidth ranging from 50MHz to 100MHz and in terms of Multiple-Input-Multiple-Output (MIMO) schemes ranging from Single-Input-Single-Output (SISO) to 2x2 MIMO and to 4x4 MIMO. In some cases, tests were performed using different Time Division Duplexing (TDD) Uplink-Downlink (UL/DL) pattern types and TDD special slot patterns, favouring UL or DL transmission depending on the UC deployment context.

The first step of the projects' testing and evaluation activities was to measure network performance in terms of DL/UL radio access network capacity, excluding the effect, capabilities, restrictions of applications running on top of network deployments. For this purpose, most of the projects used common tools such as iperf to stress the 5G Radio

Access Network (RAN) and measure the achieved peak data rates, under no additional traffic conditions. The results from the 15 projects are summarised in Figure 4.

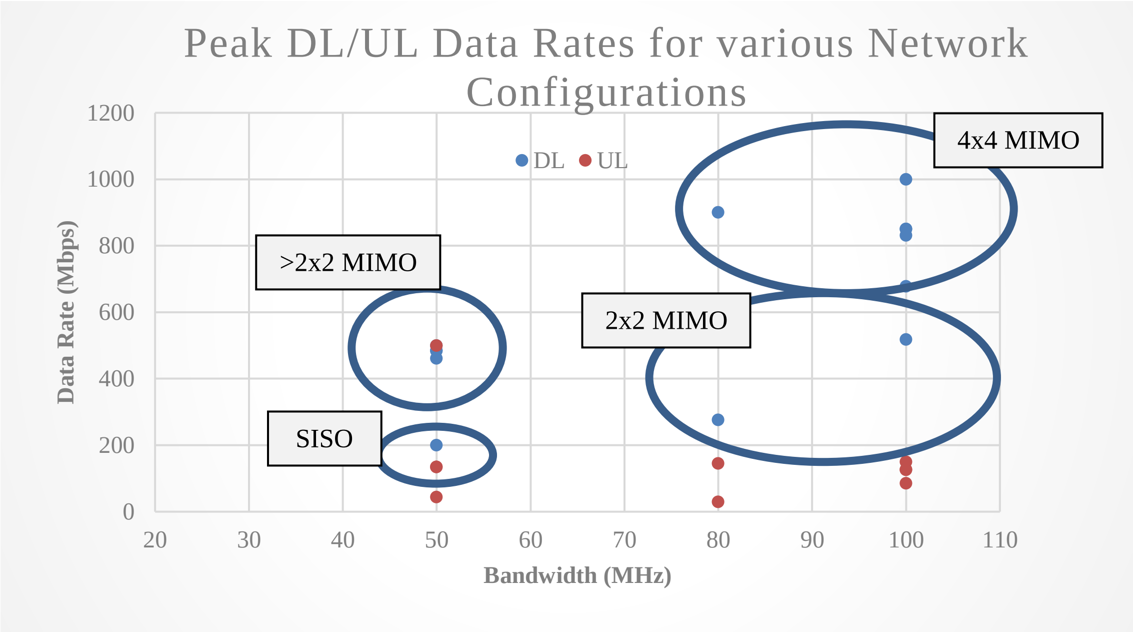

Figure 4: Peak DL/ UL Data-rates for various Network Configurations

In general, the obtained results for the DL and UL data-rates validated the theoretical maximums achievable for the different network configurations. Maximum DL data-rates of above 1Gbps and maximum UL data-rates of 500Mbps (with special TDD patterns) have been achieved. The variation of results of the various scenarios and projects depends also on the environment of the deployment and the distance between the tester and the radio node (besides the configuration specifics). Moreover, it becomes obvious that there is a direct benefit of using higher order MIMO schemes, which can compensate for the size of the channel bandwidth. The results also revealed the flexibility of 5G networks to be tailored - through appropriate configuration - to the vertical deployment needs and requirements.

4.2 User Experienced Data Rate (Downlink)

As a next step, projects performed trial campaigns focused on the relevant vertical applications and services. The 15 projects covered an extensive set of trial scenarios. Results for the User Experienced data rates in the DL have been reported for 48 scenarios in total. These scenarios focused on services related to the following vertical (sub-) sectors: media (production, distribution and services), automotive, digital mobility, smart-cities, logistics and transportation.

The obtained results seem to depend mostly on the specific vertical applications and services used, the user expectations, the imposed traffic conditions of the radio nodes, the environment and the location of the user in each setup. Therefore, the obtained results cannot be directly compared, but they can still provide significant insights with regards to the expected performance of 5G in various scenarios, the expected range of user data-rate requirements from the forthcoming 5G deployments, and the trends related to the user data-rate requirements in the longer term along with the scenarios and services driving these trends. The results are summarized in Figure 5. Despite the differentiation of services and testbed configurations, a comprehensive cartography has been created, relating the experienced (and expected) data-rates per service and vertical sector, as depicted in Table 4.

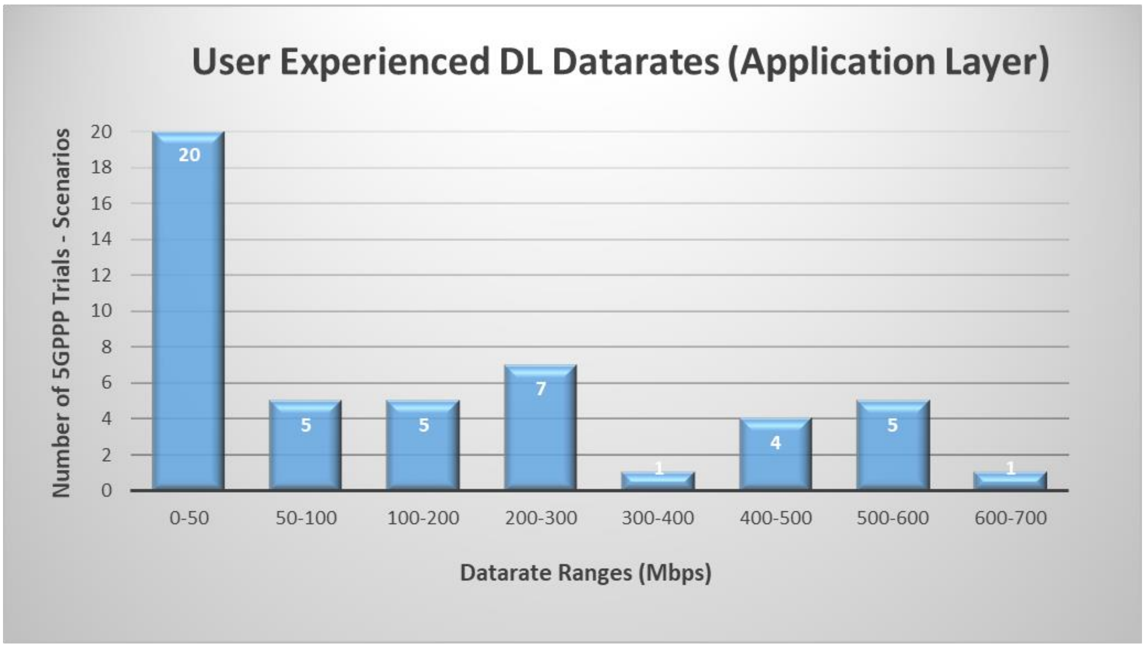

Figure 5: User Experienced DL Data Rate Results

From Figure 5 and Table 4 it can be observed that the majority of services require relatively low DL data-rates compared to the network capacity, less than 50Mbps. These are associated with single stream video service components or with services based on UL with DL ack or command & control feedback. High demanding applications requiring data rates between 50-250Mbps are associated with enhanced single- or multi- stream media services and synthetically produced eMBB services. Services of these two performance categories, with versatile content and in different contexts, are applicable in UCs of all verticals (excluding the smart factory for which services limited to <50Mbps have been examined).

Services of higher data rates (between 300Mbps and as high as 900Mbps) are considered pre-6G services (such as immersive communications, augmented experience etc.) with high fidelity, multi- stream video service components – for various purposes- or services sourcing data from multiple streams for post-processing (e.g., via AI/ML) and service delivery. Key verticals addressed by such services are the media, automotive, transportation and logistics as well as advanced mission critical / PPDR. In all cases the video components of the services drive the data rate requirements trends. At this point it shall be noted that taking into account cross-vertical services and relationships, and the details of each trialled application the mapping between particular services and verticals may deviate slightly from the UC-verticals mapping of Table 3.

4.3 User Experienced Data Rate (Uplink)

In parallel, projects covered an extensive set of trial scenarios, focusing on the User Experienced data rates in the UL. Results of the 15 projects have been reported for 41 scenarios in total. These scenarios are: media (production, distribution and services), automotive, digital mobility, smart-cities, logistics and transportation.

Similarly to User Experienced DL data-rates measurements, the obtained results depend mostly on the specific vertical applications and services used, the user expectations, the imposed traffic conditions of the radio nodes, the environment and the location of the user in each setup. Therefore, the obtained results although not directly comparable, they can provide significant insights with regards to the expected performance of 5G in various scenarios, the expected range of user data-rate requirements from the forthcoming 5G deployments in short term, and the trends related to the user data-rate requirements in the longer term along with the scenarios and services driving these trends. The results are summarized in Figure 6. Despite the differentiation of services and testbed configurations, a comprehensive cartography has been created, relating the experienced (and expected) data-rates per service and vertical sector, as depicted Table 5.

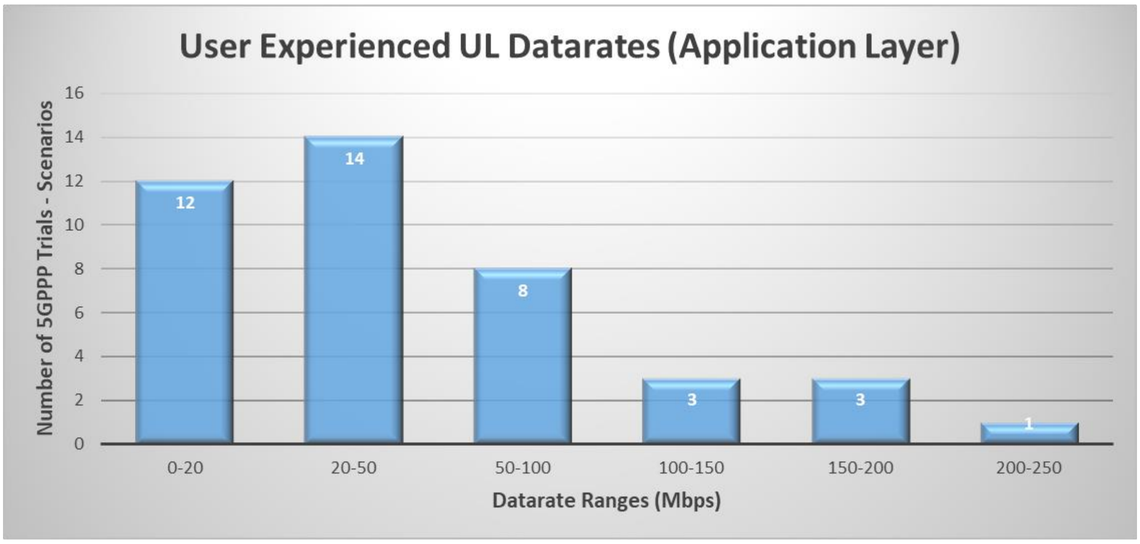

Figure 6: User Experienced UL Data Rate Results.

The numeric results indicate that the majority of the applications/ services are delivered with relatively low, less than 50Mbps, User Experienced UL data rates (26 out of 41 scenarios in total), as this data rate is related to feedback/acknowledgement, or standard quality video. Data rates between 50-100 Mbps usually concern enhanced surveillance, AR/VR and immersive applications, while services demanding more than 100Mbps fall in service categories such as PPDR, preventive maintenance and incident detection.

By observing Figure 6 and Table 5 combined it can be understood that in the UL, services required less than 50Mbps for typical 5G applications of all verticals. The highly demanding applications with above 50Mbps correspond to future (6G) services such as Digital Twinning, AR/VR and immersive communications or as multiple sessions data transfer, and are associated with media, automotive, transportation and logistics as well as advanced mission critical / PPDR verticals as in the case of DL experienced data rates.

Table 4: Mapping of Verticals, Services and User Experienced DL Data Rates in 5G PPP projects (2022 Trials)

DL DR / Vertical	**0-50 Mbps**	**50-250 Mbps**	**250-400 Mbps**	**>400 Mbps**
Generic Service Characteristics	**Single stream video** **Services based on UL with DL ack or command & control feedback**	**Enhanced single- or multi- stream media services / eMBB services**	**Multi- stream video services** **Multi stream video or other data delivered for processing and service delivery**	
Media Verticals	Live TV production services (5G-RECORDS), HD video, telepresence, guidance services (e.g. Robo-assisted museum guide) (5G-TOURS), vCDN (single stream) (5G-COMPLETE)	AR/VR tourist services (5G-TOURS), vCDN services (5G-VICTORI).	Smart glasses and ultra sound services, (5G-TOURS)	Augmented tourism experience (5G-TOURS), Immersive application / 360° tour guide (5G-VICTORI)
Automotive	Teleoperation, Command & Control Data & instructions to vehicles (5GASP)	eMBB services to automotive passengers (synthetic traffic) (5G-MOBIX), C-ITS (5GASP, 5G-TOURS)	eMBB services to automotive passengers (5G-MOBIX, 5GCroCo) CACC-based platooning and Remote takeover (5G-Blueprint)	eMBB services to automotive passengers (synthetic traffic) (5G-MOBIX, 5GCroCo), Digital Twinning (5GASP)
Transportation & Logistics	Teleoperation (vessels/trucks) at ports (5G-Blueprint)	eMBB services to railway passengers (synthetic traffic) (5G-VICTORI), Smart airport services (parking) (5G-TOURS)	Warehouse logistics (VITAL-5G), Vessel transport, and Port Navigation (VITAL-5G, 5G-Blueprint), CCTV, Rail Signalling and Rail Critical Services (Telephony) over 5G network (5G-VICTORI)	
Mission Critical / PPDR	Mission Critical and Business Critical services, Civil defence AR based remote team leading, object tracking (5G-EPICENTRE)	Situational Awareness supporting CCC operations in the field (5G-EPICENTRE),	Emergency airport evacuation (5G-TOURS) Isolated Operations for Public Safety (IOPS) (5GASP)	Remote surveillance (5G-EPICENTRE)
Smart factory	Command & Control Data (5G-VICTORI)			
Smart Cities	Ack for Clinical apps with remote support (5G-EPICENTRE)	Digital mobility, infotainment and smart assistance services (5G-VICTORI, 5G-TOURS), Health Assistance / Ambulance routing services (5G-TOURS)		

Table 5: Mapping of Verticals, Services and User Experienced UL Data Rates in 5G PPP projects (Trials 2022)

UL DR / Vertical	*0-20 Mbps*	*20-50 Mbps*	*50-100 Mbps*	*>100 Mbps*
Service Characteristics	**Single stream video** **Services based on DL with UL ack or command & control feedback**	**AR/VR video** **Multi stream video service components**	**AR/VR and immersive services** **Data capturing for further AI/ML Processing**	
Media	Live TV Production Services (5G-RECORDS)	AR/VR tourist services (5G-TOURS),	Multicam live production (5G-RECORDS) Smart Glasses & ultra sound, Multi-stream digital ultrasound data transfer (5G-TOURS)	AR/VR and immersive 360° tour services (5G-VICTORI).
Automotive	V2X synthetic data, In-vehicle processed data for teleoperation/ remote driving / vehicle remote assistance, centralized C-ITS (5GASP)	Automotive applications (synthetic traffic) (5G-MOBIX, 5GCroCo, 5G-TOURS)		Digital twinning (5GASP), Automotive applications (using synthetic traffic) (5GCroCo)
Transportation & Logistics	Smart airport parking management (5G-EPICENTRE)	Vessel transport (VITAL-5G) Teleoperation (vessels/trucks) at ports (5G-Blueprint)	Warehouse logistics (VITAL-5G)	CCTV, Rail Signaling and Rail Critical Services (Telephony) (5G-VICTORI), Port Navigation (VITAL-5G)
Mission Critical / PPDR	Mission Critical and Business Critical services (5G-EPICENTRE) Advanced surveillance services, object tracking (5G-COMPLETE)	Civil Defence assisted by AR, Situational Awareness Services supporting CCC operations in the field (5G-EPICENTRE) Recognition and identification of emergency situation (5G-VICTORI) Emergency Airport evacuation (5G-TOURS)	Enhanced surveillance (drone assisted) (5G-EPICENTRE)	Fire Detection and Ground Assistance using Drones, Isolated Operations for Public Safety (IOPS) / PPDR (5GASP)
Smart factory	SD video for monitoring (5G-VICTORI)			
Smart Cities		Clinical apps with remote support e.g. Stroke/ heart attack/trauma diagnosis/support; treat at scene; USAR/CBNRE commander support (5G-TOURS, 5G-EPICENTRE) Infotainment (5G-VICTORI)		

4.4 Network Latency

Regarding latency, 50 scenarios from the 15 projects were analysed in total and the findings are reported in Figure 7. In detail, all the trial scenarios which are executed on 3GPP Rel.15 and Rel.16 deployments (either NSA or SA) illustrate Round-trip time (RTT) latencies of below 30ms, with an average around 18ms. Almost 1/3 of all scenarios present RTT latencies in the range of 15-20ms. It is also important to stress that 32 of the total 50 trial scenarios demonstrate RTT latencies below 20ms validating the latency performance of 5G deployment.

In addition, the 3GPP SA deployments depict clearly better RTT latency against the 3GPP NSA deployments. The vast majority of the SA results are concentrated in the range 0-15ms with only a few of them in the range 15-20 or higher. In the NSA case the situation is inverted, almost all the results are concentrated in the range 15-30ms, with only two cases below 15ms. The analysis on the service deployment approach (central or edge) illustrates that the latency performance is highly related with the specificities of the scenario (the actual path of the traffic flows) and the deployment configurations and should be studied case by case.

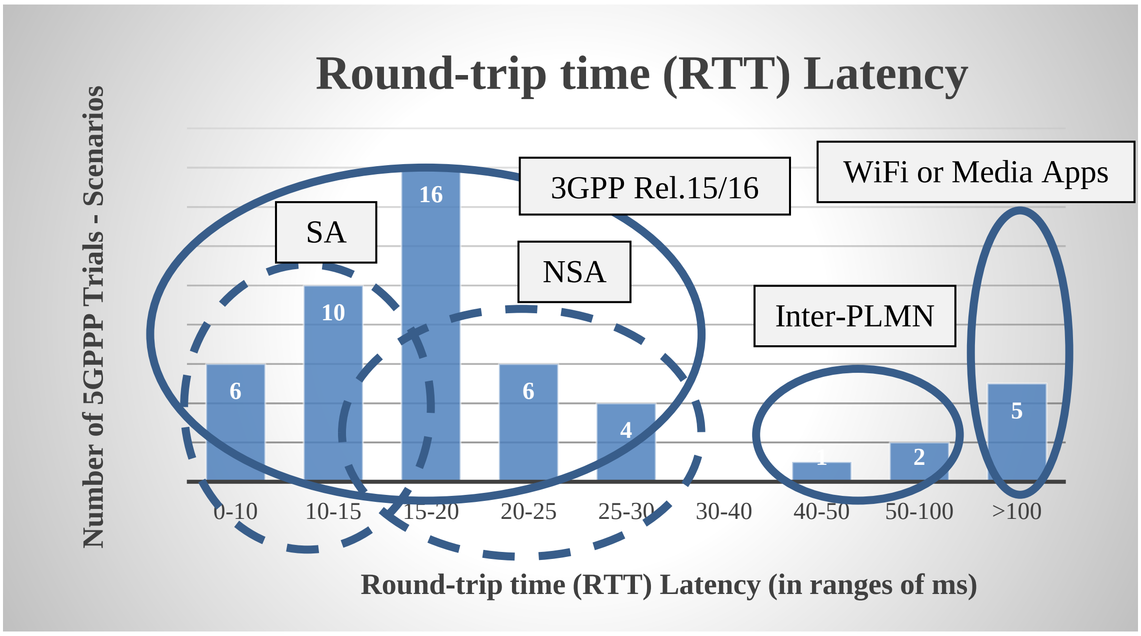

Figure 7: Network RTT latency for various scenarios

As illustrated in Figure 7, some of the trial scenarios (8 out of 50) demonstrate RTT latencies higher than 30ms. The analysis of these scenarios in terms of a) deployment environment; b) involved technologies and c) application particularities revealed the reasons lying behind these values. In detail, values in the range of 40 to 100ms, were captured by trials scenarios related to inter-PLMN cross-border automotive transitions, something that justifies the high latencies assuming signalling exchanged between two 5G core networks. In the cases of latency values above 100ms, two reasons are identified. The first is related with the use of WiFi technologies for collecting the application traffic before aggregating in the 3GPP Rel.15 and Rel.16 deployments. The second reason is related with the needs of the media applications which requires the introduction of media components in the end-to-end path of the media flows. These components (based on their functionalities) introduce significant latency into the media flows.

Regarding the tools for measuring latency, in the majority of the scenarios the iperf and ping tools were used to measure RTT latency. In many scenarios, additional tools were used in combination with the above, in order to collect additional data. In detail, open source and commercial tools were used (mostly following the TWAMP protocol) to measure One Way Delay (OWD), while in selected scenarios specialised tools and probes were used to measure latency in different segments of the network (e.g., radio, core, transport, inside VMs) and probes located in lower layers.

4.5 Additional KPIs

Testing and evaluation activities of the projects have also put emphasis on additional KPIs related to the specific focus areas of each project, indicatively being: performance evaluation using application-specific metrics, evaluation of orchestration frameworks for 5G, evaluation of cross-border network deployments using deployment-specific metrics, etc. From these we can distinguish jitter at application and network layers, application related latency and orchestration layer latency components as well as service interruption times in various handover scenarios.

Particularly, **jitter** is commonly measured (5G-TOURS, 5G-HEART, 5G-VICTORI, VITAL-5G, 5G-COMPLETE) either as a metric of network performance or as a metric of the application performance. Jitter values that have been measured are usually a fraction of 1 ms, although jitter values in the order of some ms have also been measured (MIN: 0.05ms, MAX: 4ms, Average: 1ms).

Application related latencies have also been measured by specific projects/ scenarios, among which we can highlight the following KPIs: (1) Latency for V2V communication (measured 18ms by 5G-Blueprint), (2) Mission Critical call setup times (measured 150ms by 5G-VICTORI) and (3) Time to request a timeslot for Mission Critical Group call (measured ~50ms by 5G-VICTORI).

Orchestration related KPIs addressed in the late Phase 3 5G PPP projects, (e.g., 5G-VICTORI, Int5Gent, 5G-COMPLETE) are: (1) Service/ Application Graph deployment times, (2) Slice deployment times, (3) VNFs deployment times, (4) 5G network RAN/Core/Transport deployment times. In general, measured deployment times are less than 10min depending on the software components and configuration scripts.

Last but not least, projects focusing on "5G for cooperative, connected and automated mobility" have put emphasis on measuring besides cross-border latencies, also **service interruption times** under various deployment scenarios. Among these KPIs the following have been measured (e.g., 5GCroCo): (1) Service interruption time with inter-PLMN handover (cross-border) measured ~122-155ms, (2) Service interruption time with Release-with-Redirect with S10 interface (cross-border) (measured ~ 726ms) or without S10 interface (cross-border) (measured x10 times greater).

5 Conclusions

As the work of the Test, Measurement and KPI Validation Working Group of the 5G PPP approaches its finalization at the end of 2023, this white paper presented the latest findings from the 5G-enabled field trials of 15 5G PPP projects. The goal of these trials has been to validate in the field the claimed performance of 5G networks under a diverse set of configurations, scenarios and environmental parameters, *in the context of versatile vertical sectors and use cases*. To that end, a multitude of metrics was measured in the field in more than ***80 5G-enabled scenarios,*** addressing around ***50 distinct use cases.*** The validation of these UCs took place in the ***36 5G-enabled trial sites*** constructed around Europe from the ***15 5G PPP projects*** that participated in this white paper.

Based on these metrics, the presented analysis focused on three main KPIs, namely peak data-rate, average user data-rate and networks latency, while it also provided insights with regards to additional, more scenario-specific KPIs. Even though the presented work focused on the overall evaluation of the 5G network performance as derived from the 5G PPP projects testing activities, additional insights were also gained with regards to the expected performance and behaviour of key vertical applications and the key aspects driving future service trends. In overall, the work performed in the afore-mentioned trials and the reported results, significantly contribute to the better understanding of the expected field performance of 5G networks, their behaviour under different configurations and environmental settings and the suitability of each 5G feature/technology per vertical application and environment. The key findings of this work, can be summarized as follows:

- In terms of ***Peak Data Rates***, the theoretical maximum of the 5G system was indeed validated in the field by recording data-rates of up to 1 Gbps in the DL and 0.5 Gbps in the UL. The added-value of MIMO was also confirmed, as it was shown that higher order MIMO provided significant benefits in terms of the achieved data-rates.
- In terms of average ***User Data Rates,*** the flexibility and reconfigurability of the 5G system was demonstrated in the various trials, as the network tailored its performance to the requirements of the vertical application, showcasing vastly different metrics based on the trialled scenario. It was clearly shown that the network adapts to the needs of the vertical UC providing varying user data rates, both in the DL and then UL. From the trialled verticals it was shown that Media, Command & Control and Automotive applications require the lower user data-rates, AR/VR, smart assistants, teleoperation and digital mobility applications have somewhat increased demands in terms of user data-rates, while multi-stream AR, PPDR and incident detection are the most demanding applications.
- In terms of ***Network Latency***, once again the theoretical 5G system target values were validated in the field as essentially all trialled applications that didn't entail special circumstances (e.g., cross-border functionality) achieved a RTT latency below 30 ms. Even more impressively, 65% of all trialled scenarios achieved a RTT latency below 20 ms. Interestingly enough, the improvements offered by 5G

SA over 5G NSA were also confirmed in the field, as measurements indicated that RTT latency dropped to around 12 ms with SA while it averaged around 30 ms for NSA. The experienced latency did indeed increase under special conditions such as inter-PLMN functionality but was still kept within reasonable bounds (<100 ms).

Besides the detailed analysis of the above main KPIs, additional insights were provided regarding the observed field performance of a handful of scenario-specific KPIs such as jitter, service interruption, mission critical call setup times, orchestration components delays and more, as well as a detailed ***mapping of the experienced user data rate in the field per vertical service***. Such insights help to better understand the intricacies of each specific vertical service, it's requirements and targeted performance as well as the potential needs for slicing in future 5G networks and indicate a potential grouping of similar services under common slices.

From jointly observing the DL and UL experienced (service) performance compared to 5G network performance it becomes apparent that currently, 5G network capabilities are sufficient and 5G will remain a viable technology solution in the forthcoming years, for the delivery even of the most demanding services, given proper network rollout in terms of coverage and capacity planning. In addition, apart from the continuously advanced audio-visual services, what seems to ***drive future trends in service performance*** requirements will be primarily service categories (PPDR, preventive maintenance, incident detection, etc.) enabled by service components performing data collection for further processing with AI/ML techniques [13].

For more than 4 years the TMV WG has been reporting on field measurements, testing and validating 5G features and technologies and providing insights with regards to measurements tools, best practices and performance metrics. With this white paper the TMV WG presents the key findings from the trials of the last active 5G PPP projects and enters its last stage of activities before its wrap-up at the end of 2023. An overview of the performed work, key achievements, highlights and lessons learned of the TMV WG over its years of operation will be provided in an upcoming 5G PPP-wide paper looking at 5G PPP's work in review, with the participation of all its working bodies (Steering Board, Technology Board and Working Groups).

Even though the 5G PPP will soon wrap-up its successful 10-year operation, new initiatives are already in place to drive the EU-based R&I activities into the Beyond 5G and 6G era, such as the Smart Networks and Services Joint Undertaking (SNS-JU)[3]. The valuable experience gained by all 5G PPP TMV WG members, the lessons learned and best practices, accumulated over its long operation will be inherited by these new initiatives to ensure the strong foundation of the testing measurement and validation procedures for the follow up R&I programmes.

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Abbreviations and acronyms

Abbreviation	Explanation
3GPP	3rd Generation Partnership Project
5G NR	5G New Radio
5G PPP	5G Public Private Partnership
6G-IA	6G Industry Association
AI/ML	Artificial Intelligence / Machine Learning
AR	Augmented Reality
B5G	Beyond 5G
CCTV	Closed-Circuit Television
C-ITS	Cooperative Intelligent Transportation Systems
DL	Downlink
E2E	End to End
eMBB	Enhanced – Mobile Broadband
GNSS	Global Navigation Satellite System
HD	High Definition
IOPS	Isolated Operations for Public Safety
ITU	International Telecommunication Union
KPI	Key Performance Indicator
MEC	Multi-access Edge Computing
MIMO	Multiple Input Multiple Output
MNO	Mobile Network Operator
ms	milliseconds
NFV	Network Function Virtualization
NGMN	Next generation Mobile Networks
NSA	Non-Stand Alone
OWD	One Way Delay
PLMN	Public Land Mobile Network
PPDR	Public Protection & Disaster Relief
R&I	Research & Innovation
RAN	Radio Access Network
RTK	Real-Time Kinematic positioning
RTT	Round-Trip Time
SA	Stand Alone
SD	Standard Definition
SDN	Software Defined Networking
SISO	Single Input Single Output
SLA	Service Level Agreement
TDD	Time Division Duplexing
TMV	Test, Measurement and KPIs Validation
TWAMP	Two-Way Active Measurement Protocol
UAV	Unmanned Aerial Vehicle

UC	Use Case
UE	User Equipment
UL	Uplink
V2X	Vehicle to Anything
VNF	Virtual Network Function
VR	Virtual Reality
WG	Working Group
xR	"Anything" Reality

Appendix – Trial Scenarios

Project - Trial Scenario Number	Scenario Title
5G-Blueprint - TS#1	5G-enhanced teleoperation of vehicles/barges. The pilot comprises port terminals and public roads, where real teleoperation is performed on the confined areas within terminals, and shadow mode teleoperation on the public roads (control is not applied at the user side). Preliminary testing Use Cases of CACC-based platooning and Remote takeover is included.
5G-Blueprint - TS#2	This Trial scenario includes the following: (1) A pilot on Schelde's right bank at Port of Antwerp Bruges, where the shadow-mode teleoperation is performed on a barge sailing from Liege to Antwerp. (2) A pilot at Transport Roosens Kallo site, which is a hub for picking up and dropping off containers from depots, where both shadow-mode testing and real teleoperation on closed roads are performed.
5GCroCo - TS#1	Corridor France - Germany (Forbach - Saarbrücken area) cross-border deployment is tested. The French 5G NSA radio cells deployed in Forbach (France) are connected to a core network hosted by Ericsson in Aachen (Germany) which is about 200 km away (air distance). The German NSA cell deployed in Saarbrücken is connected to a core network also hosted by Ericsson in Aachen. The backhaul link goes via Munich to Aachen, obtaining thus a total distance of about 860 km (air distance).
5GCroCo - TS#2	Corridor France - Germany (Forbach - Saarbrücken area) cross-border deployment (as in 5GCroCo - TS#1) is tested.
5GCroCo - TS#3	Corridor France - Germany (Forbach - Saarbrücken area) cross-border deployment (as in 5GCroCo - TS#1) is tested.
5GCroCo - TS#4	Corridor Germany - Luxembourg (Perl - Schengen area) cross-border deployment is tested.: The Luxembourgish 5G NSA radio cells deployed in Schengen (Luxembourg) are connected to a core network hosted by Post in Luxembourg City which is about 20 km away (air distance). The German NSA cell deployed in Perl (Germany) is connected to a core network hosted by Ericsson in Aachen. The backhaul link goes to Aachen via Munich. This is about a total of 910 km (air distance) away.
5GCroCo - TS#5	Corridor Germany - Luxembourg (Perl - Schengen area) cross-border deployment (as in 5GCroCo - TS#4) is tested.
5GCroCo - TS#6	Corridor Germany - Luxembourg (Perl - Schengen area) cross-border deployment (as in 5GCroCo - TS#4) is tested.
5G-EPICENTRE - TS#1	Multimedia MCX Communication and Collaboration Platform enabling to provide broadband multimedia mission and Business critical services on top of 5G (and later 6G) using services like slicing, QoS and Ultra-Reliable Low-Latency Communication

5G-EPICENTRE - TS#2	Multi-agency and multi-deployment mission critical communications and dynamic service scaling. The MCX communications system aims to explore different 5G scenarios in each Trial Site by analysing the experimentation results. QoS in 4) and instantiation in 2).
5G-EPICENTRE - TS#3	Surveillance of an emergency service case from a remote position in order to improve the on-site service operation planning with first responders through autonomus control of drone flight functions in order to focus on the control of the video camera angle and position.
5G-EPICENTRE - TS#4	Situational awareness Network Application (Mobitrust) supporting Command and Control Centre (CCC) operations to obtain full awareness from the field. It provides capabilities to Mobile CCC and CCC. It allows monitoring PPDR agents with End-User Devices (e.g., BodyKit (BK) Devices) in the field, by retrieving and collecting data from different types of sources: agent bio-sensors (e.g., ECG, SpO2, respiration rate), geographical/indoor positioning, internal communication systems, vehicles (e.g., ambulances), devices (e.g., drones), and real-time text, audio, and video transmissions. Data is then relayed over 5G and processed in the server to be displayed in the CCC at the operator's request.
5G-EPICENTRE – TS#5	Wearable, mobile, point-of-view, wireless video service delivery. End to end Service from User Equipment to Hospital emergency center. Integration of priority using Rx/N5 interface. Slice backhaul using MPLS/BGP/VPN. Clincal Applications where remote support is valuable include (1) Stroke diagnosis and support; (2) heart attack diagnosis and support; (3) trauma support; (4) treat at scene; (5) USAR/CBNRE commander support
5G-EPICENTRE – TS#6	Object Detection. OPTO generates an image flow from a camera-based system connected to the 5G network (HHI 5G Berlin), transferring the data via and VNF AI Analyzer to an 5G connected handheld display device. AI-Analyzer, hosted in 5G-Core-Serverlandscape, is annotating detected Objects in the image flow stream, which can be displayed at the 5G connected handheld display device.
5G-EPICENTRE - TS#7	A set of civil defence workers wearing Smart Glasses will be able to see Augmented Reality (AR) information when on the disaster scene. The AR layer is composed of information locally elaborated into the wearable processing unit together with information remotely elaborated by Machine Learning (ML) algorithms in the Command & Control Centre (CCC). The Smart Glasses worn by the operator send an audio/video stream to the CCC. In the CCC a remote team leader can analyse the different information coming from the disaster field.
5G-EPICENTRE - TS#8	AR-assisted emergency surgical care: First aid responders on disaster sites, using AR devices, will be able to project deformable objects (e.g., bones, arteries, organs) on top of the patient as well as obtain step-by-step instructions for critical medical operations.
5G-HEART - TS#1	Sensory data monitoring (Megara, Oslo)

5G-HEART - TS#2	Surveillance and Underwater Cameras data monitoring (Megara, Oslo)
5G-HEART - TS#3	Automation and actuation functionalities - Drone Monitoring (Megara)
5G-MOBIX - TS#1	Cross-border corridor deployment is tested with synthetic traffic across a route in an inter-PLMN cross-border between two NSA networks that are interconnected with the release with redirect with S10 interface and home routed.
5G-MOBIX - TS#2	Cross-border corridor deployment is tested. with synthetic traffic across a route in an inter-PLMN cross-border between two NSA networks that are interconnected with the release with redirect with S10 interface and home routed.
5G-MOBIX - TS#3	Cross-border corridor deployment is tested. Analyze the flow of CAM messages between two vehicles involved in an overtaking maneuver circulating in an inter-PLMN cross-border between two NSA networks that are interconnected with the release with redirect with S10 interface and home routed.
5G-MOBIX - TS#4	Cross-border corridor deployment (as in 5G-MOBIX) is tested with local breakout roaming configuration.
5G-MOBIX - TS#5	Measure the throughput near eNB/gNB locations. Testing Home Routing via Internet-based inter-PLMN connection scenario
5G-MOBIX - TS#6	Measure the throughput near eNB/gNB locations. Testing Home Routing via leased line-based inter-PLMN connection scenario
5G-RECORDS - TS#1	Lab Trial - Live Audio Production
5G-RECORDS - TS#2	Field Trial - Live TV Production
5G-RECORDS - TS#3	Kopenhagen Tivoli - Multicam live production (UE - camera)
5G-TOURS - TS#1	Smart airport parking management
5G-TOURS - TS#10	Smart glasses and ultrasound Android application with XpertEye webrtc screen sharing
5G-TOURS - TS#11	Multi-stream digital ultrasound data transfer
5G-TOURS - TS#12	Wireless operating room
5G-TOURS - TS#13	Optimal ambulance routing.
5G-TOURS - TS#2	Video-enhanced follow-me moving vehicles
5G-TOURS - TS#3	Emergency airport evacuation
5G-TOURS - TS#4	Excursion onAR/VR -enhanced bus
5G-TOURS - TS#5	Augmented tourism experience
5G-TOURS - TS#6	Telepresence
5G-TOURS - TS#7	Robot-assisted Museum guide
5G-TOURS - TS#8	High-quality video services distribution
5G TOURS - TS#9	Health monitoring and incident-driven communications prioritization
5G-VICTORI - TS#1	Deliver to passengers, location-based informative content by means of an immersive application in the city centre. Delivery of a 360° tour guide via 5G at specific geolocation video spots.

5G-VICTORI - TS#2	Provisioning of several digital mobility and public safety applications, namely: App1: Infotainment/ video services in dense, static and mobile environment App2: AI recognition and identification of emergency situation App3: Prioritized communication to command and control center
5G-VICTORI - TS#3	In a smart-city/ smart-factory environment provisioning of (1) Real-time LV energy metering services for designated points of interests (2) Energy Analytics for predictive and proactive maintenance for designated points of interest
5G-VICTORI - TS#4	eMBB services to railway passengers via on-board 5G network connectivity in a railway setup.
5G-VICTORI - TS#5	Integration of vCDN solution in 5G deployment for enabling the efficient delivery of media content to railway passengers.
5G-VICTORI - TS#6	Different types of applications included in the concept of Smart Factory.
5G-VICTORI - TS#7	Support of CCTV, Rail Signaling and Rail Critical Services (Telephony) over 5G network.
5G!Drones - TS#2	Network testing
5GASP - TS#1	Digital twin of the physical OBUs, called vOBUs (virtual OBU), with the purpose of offloading from the physical OBUs computationally intensive tasks (OdinS solution).
5GASP - TS#10	Vehicle Route Optimizer (commercially “NeoBus”, by Neobility) - a dynamic pooled transportation service (Demand Responsive Transport (DRT)) solution based on minibuses (±10 seats) that is as flexible as traditional ride-sharing, while being a fraction of the price.
5GASP - TS#11	Wildfires timely detection. The Fire Detection and Ground Assistance using Drones (FIDEGAD) NetApp relies on 5G The employment of autonomous drones is envisaged to complement with the efficient surveillance of predetermined inaccessible locations. The provided conventional video and thermal vision are transmitted via 5G to the teams on the ground. Supplementary input, e.g., information from infrared sensors and speakers, may also be made available through proportional manner. Finally, the NetApp not only handles the drove live-image streaming and process but could also allow the ground units to make adjustments to the appointed flight plan.
5GASP - TS#2	vRSU (YoGoKo) tested a software-based version of the traditional RSU. The vRSU brings the support for the V2X protocol stack required for the automotive vertical use cases.
5GASP - TS#3	Testing of C-ITS-S NetApp (YoGoKo) to control and deliver V2X services securely and efficiently.
5GASP - TS#4	Interdomain mobility capabilities to the vOBUs introduced in NetApp #1 -- digital twin of the physical OBU (OdinS solution).

5GASP - TS#5	Autonomous vehicles are usually equipped with multiple 4k cameras and sensors (LIDAR and RADAR) that generate a huge amount of data to be transferred. As autonomous vehicle technologies continue to evolve, the data generated inside cars only continues to grow exponentially. Services such as teleoperation, remote driving and vehicle remote assistance that use the generated data to both estimate the status of the vehicle and build an image of its surroundings. Such services usually send back the vehicle control commands and instructions to be executed instantaneously.
5GASP - TS#6	Testing of a solution (by DriveU and BLB) that enables a remote operator to take full/partial control over an autonomous vehicle in unusual/dangerous situations that can happen on the road (e.g., let an autonomous vehicle crossing double yellow lines). Ensuring safe teleoperation and human remote assistance entails reliable transmission of high-quality real- time video with minimum latency.
5GASP - TS#7	Network testing. Efficient MEC Handover (EMHO) NetApp designed to support the other compatible NetApp(s) to improve their performance in the MEC environment.
5GASP - TS#8	PrivacyAnalyzer is a generic, cross-vertical Network Application whose functionality is to discover privacy vulnerabilities of network streams of interest. The latter can be streams from mission-critical services implemented in private networks or streams from other Network Applications. PrivacyAnalyzer could be used to detect (albeit they are encoded, see later the format detector microservice of the backend which can decode a set of common encodings) privacy-sensitive, geo-related fields within the network messages of YokoGo's Automotive Network Application.
5GASP - TS#9	The "Isolated Operations for Public Safety" (IOPS) mode of operation is defined in 3GPP Release 17. Its principal idea is in assuring high availability and resilience of the PPDR services over commercial 5G networks even in the most extreme situations (e.g., natural or man-made disasters). The 5G IOPS NetworkApp demonstrates the flexibility of the NetworkApp concept for creating network applications for PPDR vertical.
Int5Gent - TS#1	Network testing
Int5Gent - TS#2	Network testing
REINDEER - TS#1	Augmented reality for sport events
REINDEER - TS#10	Position tracking of robots and UVs
REINDEER - TS#11	Location-based information transfer
REINDEER - TS#12	Virtual reality home gaming
REINDEER - TS#13	Smart home automation
REINDEER - TS#2	Real-time digital twins in manufacturing
REINDEER - TS#3	Patient monitoring with in-body and wearable sensors
REINDEER - TS#4	Human and robot co-working
REINDEER - TS#5	Tracking of goods and real-time inventory
REINDEER - TS#6	Electronic labelling

REINDEER - TS#7	Augmented reality for professional applications
REINDEER - TS#8	Wander detection and patient finding
REINDEER - TS#9	Contact tracing and people tracking in large venues
VITAL-5G - TS#1	Sea Port of Antwerp / Assisted vessel transport
VITAL-5G - TS#2	River Port of Galati / 5G and data-enabled assisted navigation using IoT sensing and video cameras
VITAL-5G - TS#3	Warehouse in Athens / Automation and remote operation of freight logistics (warehouse logistics)
5G-COMPLETE TS#1	Solution for verticals operating distributed infrastructure facilities by providing an architectural framework to support Advanced Surveillance and Physical security services with high resilience.
5G-COMPLETE TS#2	Solution for verticals in need of flexibly deploying NPNs based on ORAN. The solution was tested with vCDN services on top of the on demand deployment of various ORAN configurations.